VLF PHASE ANOMALIES ASSOCIATED WITH SUBSTORM

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Abstract: The substorm-associated phase anomalies are observed on the trans-auroral VLF signals, OMEGA ALDRA (13.6 kHz), GBR (16.0 kHz), OMEGA N. DAKOTA (13.6 kHz) and NLK (18.6 kHz) received at Inubo, Japan. The phase anomalies are caused by energetic electrons injected from the magnetotail and/or from the outer radiation belt. The energy of the precipitating electrons is estimated from the decrease in the reflection height for the VLF wave as >150 keV. The precipitation of such high-energy electrons is observed at all local times, but is predominant at 0800, 1630 and 2230 LT. The nighttime precipitation commences almost simultaneously with the onset of the nightside magnetic bay, while the day-side precipitation is delayed by 10–100 min. It is suggested that the magnetotail-originated electrons with energy >150 keV are injected directly into the nightside auroral region and some of the injected electrons drift eastward and then precipitate into the morning and afternoon sectors. The drift speed deduced from the time delay of onset is 5°/min on the average.

1. Introduction

At the time of the magnetospheric substorm, energetic electrons ($E>10$ keV) are precipitated into the auroral ionosphere, in addition to the auroral electrons ($E=1$–10 keV) responsible for the visible aurora and the geomagnetic disturbances (PIDDINGTON, 1965; BROWN, 1966; HARTZ and BRICE, 1967; MENG, 1978). The energetic electrons produce additional ionization in the lower ionosphere below 100 km, which results in the increase in the riometer absorption and the advance in the phase of the VLF signals having been propagated through the auroral region. The riometer absorption is caused by the ionization at altitude of 80–100 km; the corresponding energy of the precipitating electrons is 10–100 keV. The VLF wave is reflected at altitude of 80 km by night and 70 km by day under the quiet conditions, and at lower altitude under the disturbed conditions (WESTERLUND and REDER, 1973). Therefore, the VLF phase anomalies associated with the substorm detect the precipitation of the energetic electrons with energy >100 keV for night condition and >200 keV for day condition.

The local time dependence of the occurrence and of the onset time of the precipitation is one of the important properties for revealing the origin of the precipitating electrons and the physical processes in the magnetosphere at the time of the magnetospheric substorm. The riometer observations showed that the precipitation of energetic electrons (E=10–100 keV) was predominant in the morning and pre-midnight sectors, and that little precipitation took place around the dusk sector (HARTZ and BRICE, 1967; JELLY, 1970; HARGREAVES and COWLEY, 1967; HARGREAVES, 1968). This local time dependence was verified by the direct measurement aboard the satellite which detected harder electrons (E>40 keV) in the morning sector and softer electrons (E>10 keV) in the pre-midnight sector (MCDIARMID and BURROWS, 1964; FRITZ and GURNETT, 1965; HONES *et al.*, 1968), while observations from the synchronous satellite ATS-1 showed increases of energetic electrons (E=50–1000 keV) at all local times correlated with the substorm (PARKS and WINKLER, 1968). The riometer observations also showed that the absorption region expands eastward and westward from the midnight sector with progression of the substorm (BERKEY *et al.*, 1974). The morning precipitation was interpreted in terms of the electrons drifting eastward from the midnight sector, where they had been injected from the magnetotail (HARGREAVES, 1968; JELLY, 1970).

The VLF phase measurement is another important ground-based technique for detecting the precipitating energetic electrons, of which energy (E>100 keV) is higher than that detected by the riometer. Although the extensive analyses have been made of the riometer absorption as mentioned above, the properties of the substorm-associated VLF phase anomalies are not fully understood except that the significant phase anomalies are closely associated with the magnetospheric substorm (WESTERLUND and SVENNESSON, 1971; SVENNESSON, 1972; WESTERLUND and REDER, 1973). In this paper we show that significant phase anomalies are often associated with the nightside magnetic bay, and reveal the local time characteristics of the precipitation of energetic electrons responsible for the VLF phase anomaly. The results will show that the precipitation is predominant in the morning and pre-midnight sectors, consistent with the riometer observation. Furthermore, the frequent precipitation is found in the afternoon to evening sectors, during which little precipitation is detected by the riometer. It is suggested that energetic electrons with energy >150 keV are precipitated at all local times with maxima at 0800, 1630 and 2230 LT. From the local time dependence of the onset time of the phase anomaly, it is deduced that the energetic electrons are injected in the midnight sector, drift eastward with the mean speed of 5°/min and precipitate in the morning and afternoon sectors.

2. VLF Wave Propagation

We use the four propagation paths shown in Fig. 1 to detect the substorm-associated phase anomalies. In Fig. 1, the paths are drawn with the straight lines connecting the transmitter and receiver sites. The concentric circles refer to the geographic latitude and the eccentric circles to the corrected geomagnetic latitude (CGL). In Table 1 are listed the transmission frequency, the location of the transmitter and

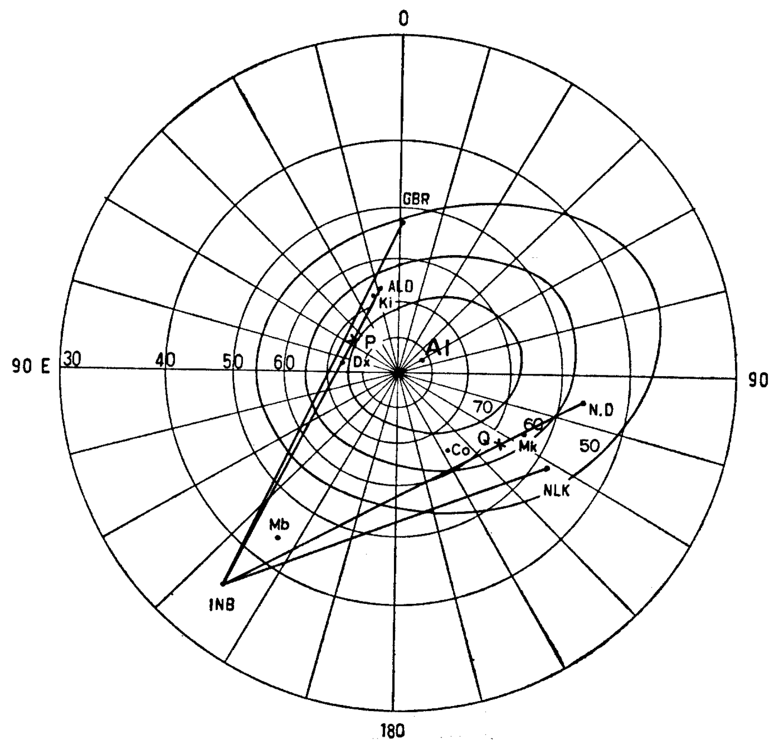

Fig. 1. *Paths from the VLF transmitter to Inubo (straight lines), and the magnetic observatories (dots) with respect to the corrected geomagnetic latitude (oval-shaped closed lines). The VLF transmitters used are OMEGA ALDRA (ALD), GBR, OMEGA N. DAKOTA (N.D.) and NLK, and the magnetic observatories are Alert (Al), Kiruna (Ki), Dixon (Dx), College (Co), Meanook (Mk) and Memambetsu (Mb). Points P and Q designated by the crosses on the ALDRA and N. DAKOTA paths represent the precipitation region (see text).*

Table 1. *Frequencies and geographic coordinates of VLF transmitter, geographic coordinates of the reception site, and distance between the transmission and reception sites.*

Transmitter	Frequency (kHz)	Transmission site (degrees)	Reception site (degrees)	Distance (km)
ALDRA	13.6	66.4°N, 13.1°E	Inubo, Japan 35.7°N, 140.9°E	7820
GBR	16.0	52.4°N, 01.2°W		9550
N. DAKOTA	13.6	46.4°N, 98.3°W		9140
NLK	18.6	48.2°N, 121.9°W		7620

the distance to the receiver site (Inubo). The substorm is defined by the magnetic bay recorded on the magnetogram from Kiruna, Dixon, Memambetsu, College, Meanook and Alert. The positions of the magnetic observatories are also shown in Fig. 1. Kiruna and Dixon are located nearly on the ALDRA path, and Meanook is on the N.DAKOTA path. The ALDRA, GBR and N.DAKOTA paths pass through the auroral zone (60–70° CGL) and the NLK path through the subauroral region. Their maximum attainable latitudes are 69, 67, 63 and 55 degrees in CGL, respectively. Therefore, the ALDRA and GBR signals can detect the high energy tail of the auroral electrons precipitating along the nightside auroral oval, while the N.DAKOTA signal detects electrons precipitated from the outer radiation belt.

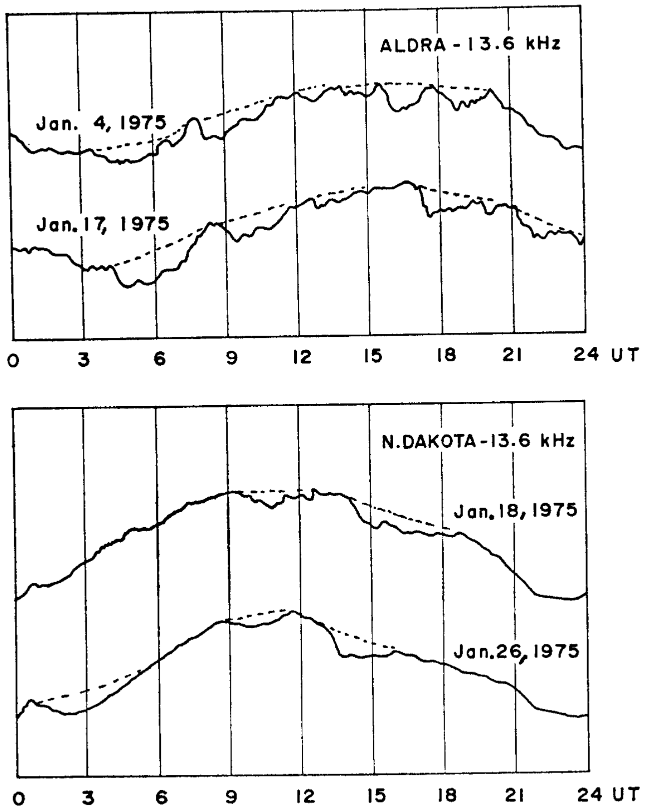

Fig. 2. Examples of the diurnal phase variations of ALDRA (13.6 kHz) and N. DAKOTA (13.6 kHz) superimposed by the substorm-associated phase anomalies. The anticipated quiettime phase levels are indicated by broken lines.

On the transpolar path signals are often observed short-term phase anomalies with time scale of one to several hours. Examples are shown in Fig. 2 for ALDRA and N.DAKOTA, where the broken curves indicate the anticipated phase level under the undisturbed condition. Most phase anomalies are advances in phase of magnitude of several to 15 μs. For the long range propagation, only the first order mode is propagated in the Earth-ionosphere waveguide because the higher order waveguide modes suffer from great attenuation compared with the first order mode (WAIT, 1962). The diurnal phase variations shown in Fig. 2 are interpreted as due to change in the phase velocity of the first order mode according to the diurnal change in the height of the reflection. However, during the sunrise and sunset transition periods we see irregular phase variations caused by the interference between the two lowest order modes if the mode conversion at the transition line is efficient (CROMBIE, 1964). Furthermore, the mode conversion can occur if the reflecting layer is horizontally inhomogeneous in such a case that the extra ionization is produced by the precipitation of energetic electrons at the time of the substorm. In the actual case, however, the non-uniform waveguide along the transpolar path causes no efficient mode conversion. Fig. 3 is an example which evidences the single mode propagation, where variations in the phase and amplitude of ALDRA are coherent with each other, with no time difference between the maxima or the minima as indicated by the arrows. As a result, the phase advance from the anticipated undisturbed level is a consequence of the lowering of the reflection height of the VLF waves, which is caused by the extra ionization produced by the energetic electron precipitation.

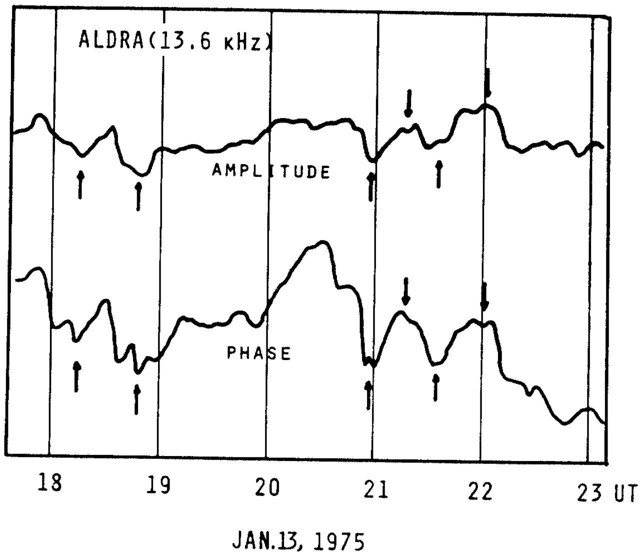

Fig. 3. Substorm-associated phase and amplitude anomalies on ALDRA. The coherency between their variations evidences the single mode propagation in the inhomogeneous waveguide at the auroral latitude.

The location of the precipitation and its horizontal extent on the path cannot be determined exactly because the phase of the received signal changes according to the ionospheric changes over the whole path. On the other hand, it is known that the precipitation is more significant with increasing latitude in the auroral region (JELLY, 1970). Therefore, we can assume that the precipitation region is represented by point P on ALDRA path and Q on N.DAKOTA path (Fig. 1), which are located at the maximum latitude on each path. This assumption enables us to determine the local time characteristics of the precipitation of the energetic electrons from the universal time dependence of the phase anomalies observed on the transpolar path VLF signals.

3. Statistical Study on Short-Term Phase Anomalies

Fig. 4 shows the occurrence frequency of the phase anomaly on ALDRA and N.DAKOTA during the period of January 1–30, 1975. The criterion for the phase anomaly is that the magnitude of the phase advance from the undisturbed level is more than 3 μs, and the duration time is 1–4 hours. We chose 79 phase anomalies from the diurnal phase variation of ALDRA and 58 phase anomalies from N.DAKOTA. The upper lines in Fig. 4 refer to all the phase anomalies and the lower lines bordering the dotted area refer to the phase anomalies correlated with the magnetic bay preceding the phase anomaly within 10 min. The maximum occurrence frequency of the phase anomaly on ALDRA is 70% at 1900 UT, when the anomalies are mostly correlated with the substorm. No direct correlation is seen around 1300 UT when the occurrence frequency of the phase anomaly amounts to over 50% (Fig. 4a). The occurrence frequency between 2130 UT and 1000 UT is much smaller (10–20%). This low occurrence frequency is partly due to the difficulty in identifying the phase anomaly from the irregular diurnal phase variation during the sunrise transition period. However, it is clear that the occurrence of the phase anomaly is not so frequent during this period, but the phase anomalies are mostly associated with the magnetic substorm. It seems that the phase anomalies around 1300 UT are not

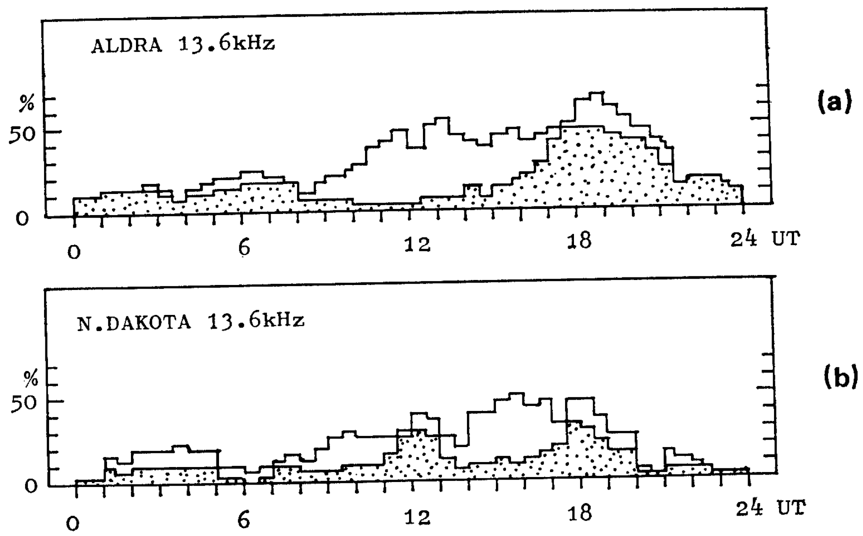

Fig. 4. Occurrence frequency of the phase anomaly on ALDRA and N. DAKOTA during the period of January 1–30, 1975. The upper lines refer to the phase anomaly of magnitude >3 μs and duration of 1–4 hours. The lower lines bordering the dotted area refer to the substorm-associated phase anomaly starting within 10 min from the onset of the nightside magnetic bay.

associated with the substorm, but as shown later, many of them are correlated with the nightside magnetic bay in such a manner that the onset of the phase anomaly is delayed from the bay onset by more than 10 min. The maximum occurrence frequency of the phase anomaly on N.DAKOTA is 50% at 1600 UT; most of the phase anomalies are not directly correlated with the substorm. However, good correlation is observed around 1200 UT and 1800 UT (Fig. 4b). The low frequency between 2000 and 0100 UT (<10%) is due to the difficulty in identifying the phase anomaly from the irregular diurnal variation during the sunrise transition period.

The UT dependence of the occurrence frequency of the phase anomaly given in Fig. 4 provides the local time characteristics of the energetic electron precipitation on the assumption that the precipitation takes place at points P and Q on the ALDRA

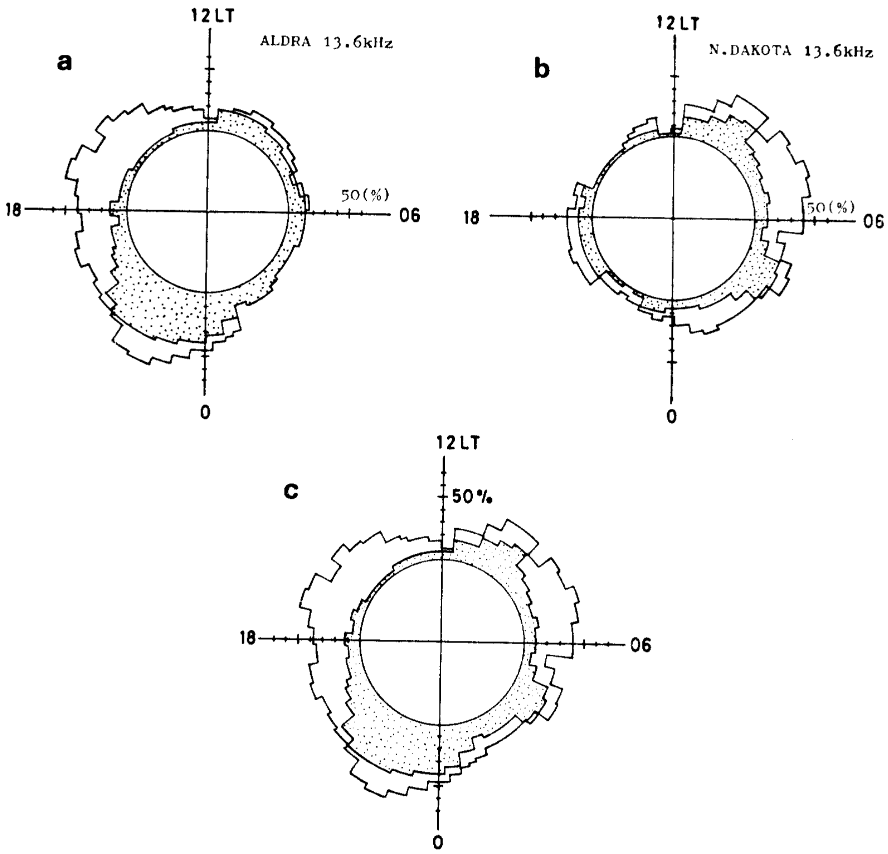

Fig. 5. Local time distribution of precipitation frequency deduced from the occurrence frequency of the phase anomaly on ALDRA and N. DAKOTA (a, b), and the combined distribution (c). The low precipitation frequency in the afternoon sector on N.DAKOTA is due to the difficulty in identifying the phase anomaly from the irregular diurnal variation. The frequent precipitation in the morning and pre-midnight sectors agrees with the riometer observation, but the significant precipitation is also observed in the afternoon to evening sector.

and N.DAKOTA paths, respectively (Fig. 1). Figs. 5a and 5b show the local time dependence of precipitation on the ALDRA and N.DAKOTA paths, respectively. In Fig. 5a, we see two peaks of occurrence of precipitation; one is directly correlated with the substorm around 2230 LT and the other is not directly correlated with the substorm around 1630 LT. The substorm-associated precipitation also occurs in the pre-noon sector. In Fig. 5b, frequent precipitation occurs from the midnight to the noon sectors. The morning precipitation is not directly associated with the substorm, while good correlation is seen in the pre-noon sector. The low precipitation frequency in the afternoon sector is due to the difficulty in identifying the phase anomaly from the diurnal phase curve. It should be noted that the precipitation frequency in the pre-midnight sector is very low, whereas in this sector the most frequent precipitation is observed on ALDRA. The discrepancy may be due to that the ALDRA path passes through the latitude of 69° CGL and the N.DAKOTA path through the latitude of 63° CGL. Consequently, the pre-midnight precipitation takes place at latitude of the auroral oval, *i.e.*, the energetic electrons are injected directly from the magnetotail along with the auroral electrons. Combining the precipitation frequency on ALDRA and N.DAKOTA (Figs. 5a and 5b), we obtain the local time distribution of energetic electron precipitation in the auroral zone as shown in Fig. 5c. The precipitation is dominant around 0800 LT and 2230 LT, in good agreement with the riometer observation (HARTZ and BRICE, 1967; JELLY and BRICE, 1967; JELLY, 1970). The remarkable feature of Fig. 5c is the predominant precipitation in the late afternoon to evening sector. In this sector the absorption anomalies are the least frequent to be observed (HARGREAVES, 1968; JELLY, 1970).

In the next section, we show the details of the phase anomaly and the close correlation with the magnetic substorm, and discuss about the delayed onset of the phase anomaly from the onset of the nightside magnetic bay.

4. Event Studies on the Substorm-Associated Phase Anomaly

In this section, we study the relation between the magnetic bay and the phase anomaly in detail from such respects as the onset time, the magnitude, and the latitude and local time of the precipitation. Detailed analyses are made for 38 substorm events. We here show several examples indicating the frequent pre-midnight precipitation on ALDRA correlated directly with the substorm, the frequent dusk hour precipitation on ALDRA with delayed onset from the onset of the substorm, no pre-midnight precipitation on N.DAKOTA and the morning precipitation on N.DAKOTA with delayed onset from the substorm onset. An example of the pre-event is also shown below.

January 4, 1975, 1200–2100 UT

Fig. 6 shows three successively occurring magnetic bays observed on the magnetic

H-components from Kiruna and Dixon, and the directly correlated phase anomalies on the ALDRA and GBR signals. The first event started at 1340 UT in Kiruna (Fig. 6a). The positive bay in Kiruna with the maximum magnitude of 400 γ lasted until 1500 UT, while in Dixon the positive bay ($\sim$250 γ) followed by the negative bay ($\sim$250 γ) started at 1400 UT. In Memambetsu the positive bay started at 1337

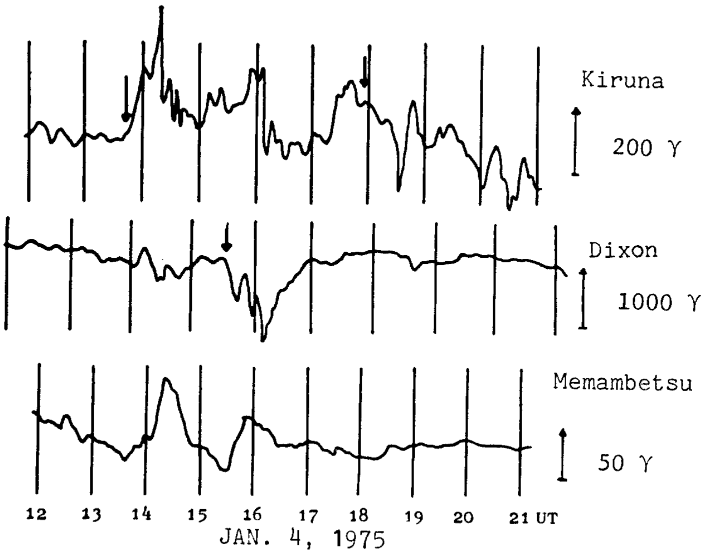

Fig. 6a. Magnetic H-components indicating the occurrence of three successive magnetic bays starting at 1340 UT (Kiruna), 1535 UT (Dixon) and 1750 UT (Kiruna) on January 4, 1975.

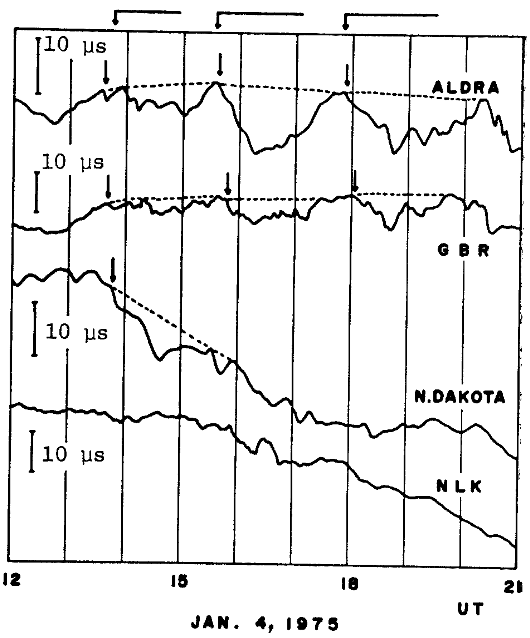

Fig. 6b. The associated VLF phase anomalies starting almost simultaneously with the magnetic bays.

UT and lasted until 1530 UT. These magnetic disturbances are produced by the eastward auroral electrojet current flowing in the afternoon to evening sectors and the westward electrojet current in the midnight sector. At 1420 UT when the negative bay started in Dixon, the buldge expanded westward beyond Dixon. The phase of ALDRA, GBR and N.DAKOTA advance from the undisturbed level in association with this substorm. The phase anomalies commenced at 1339 UT on GBR with the phase deviation of 4 μs, and at 1346 UT on N.DAKOTA with the phase deviation of 8 μs. The phase anomalies lasted until 1530 UT when the second event started. As mentioned in Section 2, these phase anomalies are caused by the precipitation of energetic electrons. If the precipitation region is represented by point P on the ALDRA path (Fig. 1), the precipitation occurs in the 1720 LT meridian at the onset of the event. In the similar manner, it is deduced that the precipitation on N.DAKOTA path (point Q) occurs in the 0520 LT meridian. The particle precipitation on ALDRA path is almost simultaneous with the development of the auroral electrojet currents, suggesting that the energetic electrons ($E>100$ keV) responsible for the VLF phase anomalies are high-energy tail of the auroral electrons. On the other hand, the precipitation on the N.DAKOTA path is somewhat delayed, which may be due to the eastward drift of the energetic electrons from the injection region in the midnight sector.

The second substorm event started at 1535 UT in Dixon. The negative bay in Dixon with the maximum magnitude of 1500 γ lasted until 1730 UT, while in Kiruna the positive bay ($\sim$110 γ) is followed by the negative bay ($\sim$150 γ). In Memambetsu the positive bay started at 1530 UT and lasted until 1800 UT. The phase of ALDRA started to advance abruptly at 1535 UT, simultaneously with the onset of the magnetic bay in Dixon; the magnitude of the phase anomaly amounts to 12 μs. The significant phase anomaly is also observed on GBR, but no distinct phase anomaly is observed on N.DAKOTA, though the phase advance caused by the first substorm event seems to be continuing. The precipitation of energetic electrons responsible for the phase anomaly on ALDRA occurs in the 1910 LT meridian. Note that the precipitation of energetic electrons occurs simultaneously with the development of the auroral electrojet currents just like the first substorm event.

The third event started at 1750 UT in Kiruna, where the negative bay with the maximum magnitude of 290 γ lasted until 1930 UT. No significant geomagnetic disturbances are observed in Dixon and Memambetsu. In spite of the small geomagnetic disturbances, the phase anomalies on ALDRA and GBR are significant; their maximum magnitudes are 10 μs and 9 μs, respectively. The onset time of the phase anomaly on ALDRA is 1750 UT and the corresponding precipitation occurs in the 2130 LT meridian. The precipitation on the ALDRA path and the development of the westward electrojet over Kiruna are simultaneous, which suggests that the high-energy electrons are injected from the magnetotail along with the lower-energy auroral electrons.

January 17, 1975, 1000–2100 UT

Fig. 7 gives an example showing the significant onset time delay between the phase anomalies on the VLF signals over the dayside paths (ALDRA, GBR) and the nightside magnetic bays (College). The intensity of the magnetic H-component in College started to decrease gradually at 1100 UT (Fig. 7a). After the gradual decrease of about 200 γ, the magnetic field abruptly decreased at 1200 UT, reached the maximum deflection of about 700 γ at 1220 UT, then recovered to the quiettime level at 1400 UT. We note that the positive bay in Memambetsu started around 1200 UT, whereas the negative bay in Meanook started around 1115 UT. The phase of N.DAKOTA began to advance at 1200 UT, simultaneously with the onset of the steep magnetic decrease in College and with the onset of the positive bay in Memambetsu. The magnitude of the phase anomaly is 9 μs. The responsible

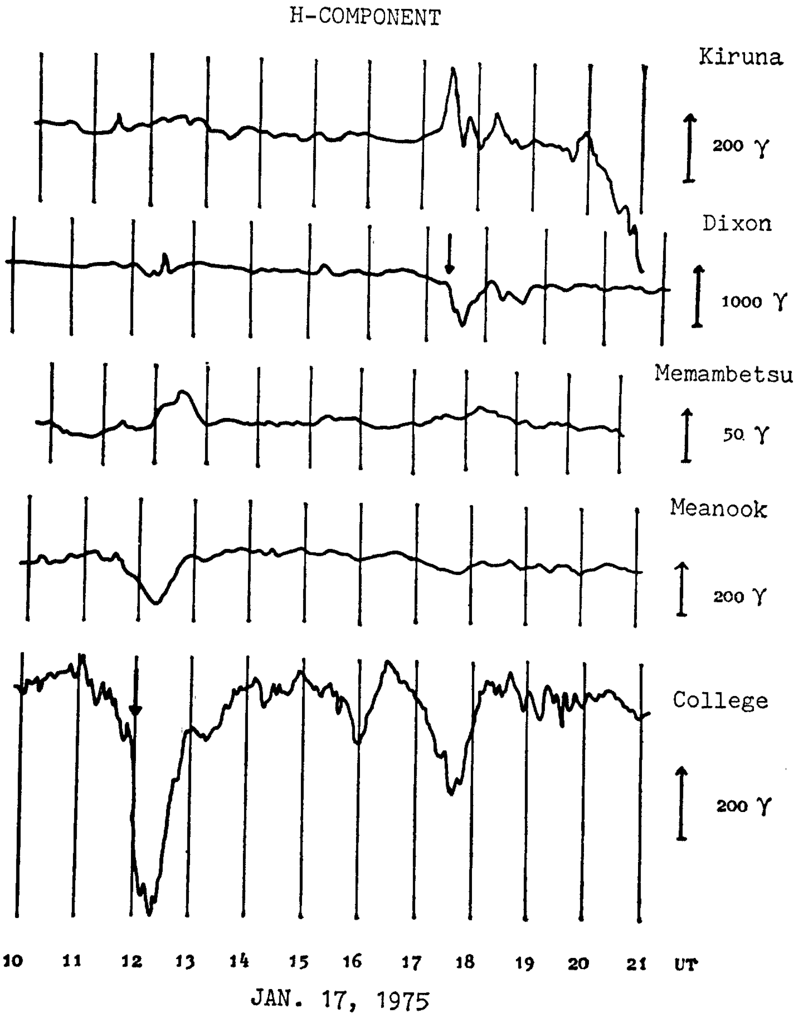

Fig. 7a. Magnetic H-components indicating two successive magnetic bays starting at 1200 UT (College) and 1720 UT (Dixon) on January 17, 1975.

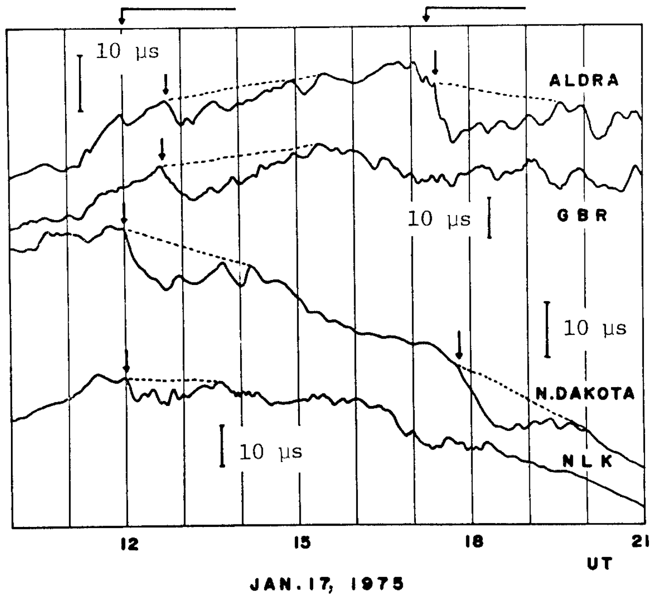

Fig. 7b. The associated VLF phase anomalies with simultaneous onset on the nightside paths and with delayed onset on the dayside paths.

electron precipitation occurs in the 0340 LT meridian. Note that the precipitation region extends to the subauroral region, as evidenced by the simultaneous phase anomaly on NLK. The precipitation continues until 1400 UT when the magnetic H-component in College recovers to the quiettime level. A slight phase advance is observed on ALDRA at 1200 UT, but the major phase anomalies start at 1244 UT on ALDRA and 1238 UT on GBR. The responsible precipitation occurs on the ALDRA path in the 1540 LT meridian. It should be noted that the onset of precipitation on ALDRA is delayed from the onset of the precipitation on N.DAKOTA by about 44 min.

The simultaneous onset of the negative bay in College and the phase anomalies on N.DAKOTA and NLK suggests that energetic electrons ($E>100$ keV) are precipitated from the Van Allen radiation belt into the auroral and subauroral regions in the post-midnight sector, simultaneously with the auroral electrons of $E<10$ keV responsible for the electrojet current. The difference in the onset time of the phase anomaly on ALDRA and of the nightside magnetic bay may be caused by the eastward drift of energetic electrons injected in the midnight sector. If we assume that the injection occurs in the 0000 LT meridian and the precipitation on the ALDRA path occurs in the 1620 LT meridian, 44 min after the injection, we obtain the drift speed of 5.6°/min.

The other substorm took place at 1720 UT in Kiruna where the positive bay with magnitude of 200 γ is observed. Almost at the same time the negative bay with magnitude of 750 γ is observed in Dixon. In association with this substorm, the phase of ALDRA and N.DAKOTA are severely disturbed, but no disturbances are observed on GBR and NLK signals. The phase anomaly on ALDRA commenced abruptly at 1725 UT, just after the onset of the substorm. On the other hand, a gradual phase advance of magnitude of 8 μs started at 1745 UT on the N.DAKOTA signal. The responsible precipitation begins to occur in the 2100 LT meridian on the ALDRA path and in the 0900 LT meridian on the N.DAKOTA path. The simultaneity of the onset of the phase anomaly on ALDRA and the magnetic bay suggests that the precipitation of the energetic electrons in the evening sector occurs simultaneously with the development of the electrojet current like the three successive substorm events shown in Fig. 6. The time delay of 25 min of the onset of the phase anomaly on N.DAKOTA from the substorm onset is due to the eastward drift of energetic electrons. If the electrons drift from the midnight sector to the 0900 LT meridian for 25 min, the drift speed is 5.4°/min, which is in good agreement with 5.6°/min obtained for the previous substorm starting at 1200 UT (Fig. 7).

No distinct phase anomalies on GBR and NLK in association with the 1720 UT substorm provide us with important information concerning the latitudinal characteristics of the electron precipitation. The significant phase anomaly on ALDRA implies that the energetic electrons precipitate around 2100 LT meridian in the auroral zone of $\sim$69° CGL. The precipitation region does not, however, extend to the lower latitude region ($\sim$67° CGL) traversed by the GBR path. This indicates no electron precipitation from the trapped radiation zone, which is in good agreement with the statistical results of little precipitation on N.DAKOTA around 2100 LT (Fig. 5b). We notice, however, that in other cases coherent phase anomalies are often observed on ALDRA and GBR as shown in Fig. 6. No phase anomalies on NLK indicate that the drifting electrons do not precipitate into the subauroral region around the 0900 LT meridian, while the direct injection into the 0300 LT meridian extends to the subauroral region as shown in the previous 1200 UT event.

January 17, 1975, 0000–1200 UT

Fig. 8 gives an example showing no precipitation on N.DAKOTA in the evening hours. The thick curves in the figure indicate the phase of the VLF signals recorded on January 17, 1975, and the thin curves the quiettime mean phase. The onset and the duration of the magnetic bay in Meanook are indicated by the arrows on the upside of the figure. Two substorms occurred successively; the first one started at 0400 UT and the second at 0800 UT.

In association with the first substorm, the phase of ALDRA advances abruptly at 0425 UT, 25 min after the bay onset. The magnitude of the phase anomaly is about 10 μs. Only a small phase anomaly is observed on GBR, and no anomalies on N.DAKOTA and NLK. The precipitation on ALDRA occurs in the 0805 LT meridian. The delayed onset of the phase anomaly is due to the eastward drift of the energetic electrons from the midnight to the 0805 LT meridian. Thus we obtain the

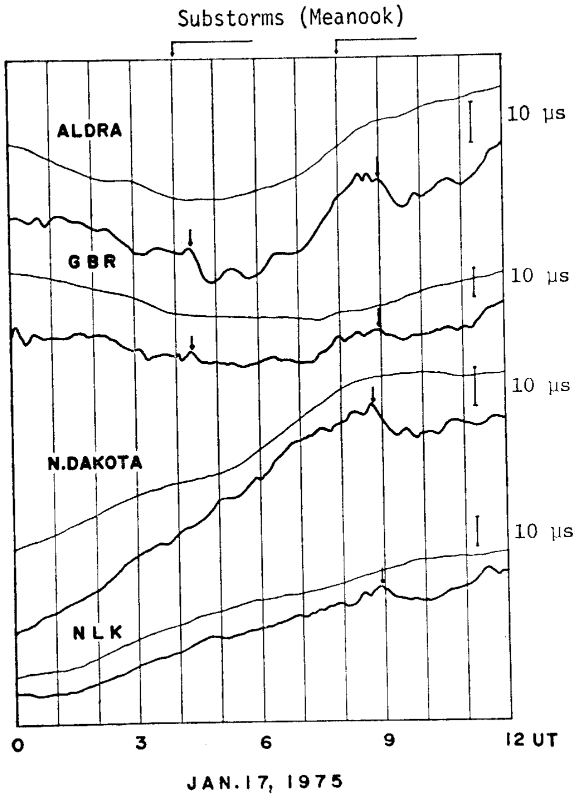

Fig. 8. Substorm-associated VLF phase anomalies with delayed onset from the substorm onset observed on January 17, 1975. The thin curves indicate the mean quiettime phase. The onset (0400 UT, 0800 UT) and the duration of the substorms are indicated by the arrows on the upside.

drift speed of 4.8°/min, which is in the same order as obtained before. At the onset of the phase anomaly on ALDRA, the precipitation region on N.DAKOTA path is located in the 2005 LT meridian. Therefore, no phase anomalies on N.DAKOTA and NLK infer that no appreciable precipitation takes place in the evening sector from the radiation belt. This aspect of precipitation is seen in many other cases as shown in Fig. 5b.

January 22, 1975, 1200–2100 UT

Fig. 9 shows an example of the "pre-event" which precedes the phase anomaly associated with the substorm. The magnetic H-component in Kiruna started to increase steeply at about 1645 UT (Fig. 9a), when the phase of ALDRA advanced abruptly. The phase advance reaches the maximum of about 10 μs at the time of the maximum increase in the magnetic H-component in Kiruna. The precipitation responsible for the phase anomaly on ALDRA occurs in the 2025 LT meridian, covering the lower latitude region traversed by the GBR path. The phase of N.DAKOTA advances significantly in association with the substorm, but the onset is obscured by the phase anomaly preceding the event. Before the bay event, the magnetic activity is quite low in all the magnetic observatories shown in Fig. 9a. However, a small but clear phase advance is observed on GBR at 1423 UT, 142 min before the onset

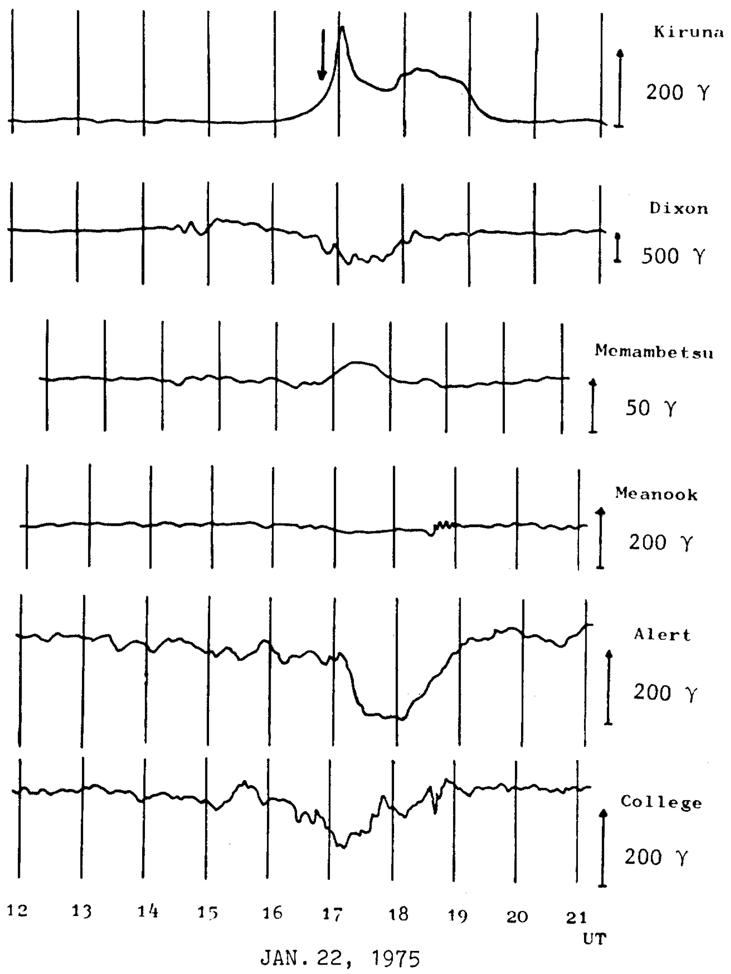

Fig. 9a. Magnetic H-components indicating the occurrence of a magnetic bay starting at about 1645 UT (Kiruna) on January 22, 1975.

of the substorm. The phase of ALDRA also advances almost simultaneously with that of GBR. A more significant phase anomaly started on N.DAKOTA at 1440 UT, when a small phase anomaly is also observed on NLK. This event may be called "pre-event" (JELLY, 1970; HARGREAVES *et al.*, 1975).

The precipitations responsible for the pre-event occur in the 1800 LT meridian on the ALDRA path and in the 0620 LT meridian on the N.DAKOTA path. The time delay between the onset of the phase anomalies leads to that the precipitation on N.DAKOTA is delayed by 17 min from that on ALDRA. It should be noted that this feature is similar to that in the first event on January 4, 1975, though the latter is directly associated with the substorm. Therefore, we can consider, as one possible mechanism, that the high-energy electrons are injected from the magnetotail, accompanying no lower-energy electrons responsible for electrojet currents, and some

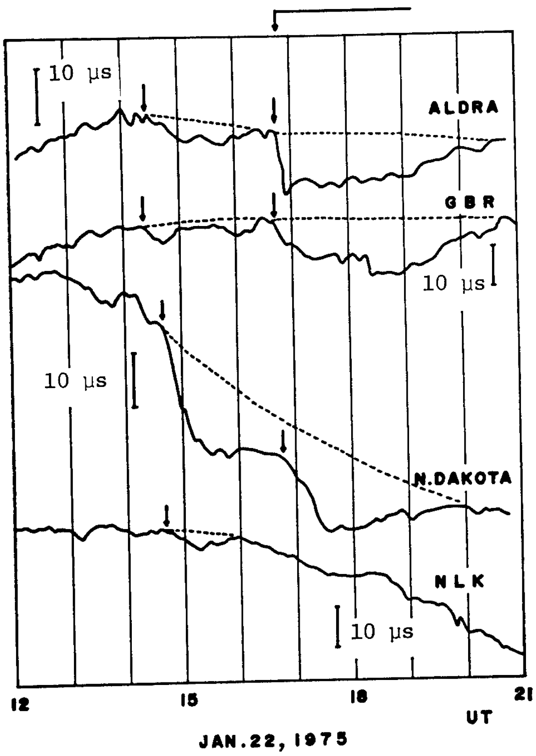

Fig. 9b. The associated VLF phase anomalies. The substorm-associated phase anomalies are preceded by significant phase anomalies.

of the injected electrons drift eastward to the meridian of the precipitation region on N.DAKOTA. However, the phase anomaly on N.DAKOTA is too large to be attributed to the drifting electrons. Consequently, it may be reasonable to consider that the primary source for the precipitation on N.DAKOTA and NLK is in the radiation belt. The phase anomalies on the ALDRA and GBR could also be caused by the electrons precipitated from the outer radiation belt.

5. Discussion

It has been shown that energetic electrons precipitate in the region centered at 2230 LT meridian on the ALDRA path, and 0300 LT meridian on the N.DAKOTA path, simultaneously with the nightside magnetic bay (Fig. 5). The nighttime lower ionosphere in the auroral zone is ionized by precipitating energetic electrons even during the magnetically quiet period (WESTERLUND and REDER, 1973). This is evidenced by the direct rocket measurements of the electron density at Syowa Station (69.0°S, 39.6°E), Antarctica, showing higher electron contents at altitude below 100 km than observed at the middle and low latitudes under magnetically quiet conditions (OGAWA *et al.*, 1978). The nighttime reflection height for the VLF wave, therefore, is somewhat lower in the auroral zone than at the middle and low latitudes. WESTER-

LUND and REDER (1973) assumed that the nighttime reflection height for the VLF waves is 80 km at the auroral latitude, while the reflection occurs at 90 km height at the middle and low latitudes (WAIT, 1962). The energetic electrons ionizing the lower ionosphere below 80 km need the energy more than 100 keV (REES, 1964).

We now estimate the energy of the precipitating electrons from the magnitude of the phase anomaly observed on ALDRA. As mentioned in Section 2, only the first order mode is propagated in the auroral zone where the width of the waveguide is narrower than that outside the auroral zone. We first assume that the electron precipitation occurs uniformly over the auroral region of latitude $>60°$ CGL. Then, the path length affected by the precipitation is 4100 km of the total path length of 7820 km. The waveguide mode theory assuming the isotropic homogeneous ionosphere (WAIT, 1962) provides us with the relation between the height decrease Δh(km) and the corresponding phase advance $\Delta\phi$(μs/Mm) for the frequency of 13.6 kHz as

$$\Delta\phi = 0.47\ \Delta h. \tag{1}$$

The typical substorm-associated phase anomalies are of magnitude of 10 μs or 2.4 μs/Mm if normalized over 4100 km. Substituting this value in eq. (1), we obtain

$$\Delta h = 5.1\ \text{km}. \tag{2}$$

Consequently, the reflection height at the time of the substorm decreases to be 75 km on the assumption that the quiettime reflection height is 80 km. On the other hand, there is another choice for the precipitation region. JELLY (1970) showed that intense absorptions with sharp onset are observed in the region of $>65°$ invariant latitude, and less intensive absorptions at lower latitudes. This is evidenced by the little phase anomaly sometimes observed on GBR, whereas a significant one is observed on ALDRA (Figs. 7 and 8). If the region of $>65°$ CGL is under the influence of precipitation, the path length affected becomes 2800 km, then we have

$$\Delta h = 7.6\ \text{km} \tag{3}$$

for the phase advance of 10 μs. In this case, the reflection height is 72.4 km. The energy of electrons which ionize the lower ionosphere of height of 75 km is 140 keV and of 72 km is 190 keV (REES, 1964). Therefore, the nighttime lower ionosphere is ionized by the electrons of energy more than about 150 keV at the time of the substorm. When the ionosphere is illuminated by the sun, the reflection height is about 70 km under the quiet condition. The electron energy responsible for the ionization in the daytime ionosphere is more than 200 keV. Fig. 5 shows the frequent precipitation of such high-energy electrons around noon meridian.

The nightside precipitation is almost coherent with the development of the electrojet currents, but the dayside precipitation is often delayed from the onset of the nightside magnetic bay, as shown in the previous section. The delay time obtained from 38 events during January 1975 is shown in Fig. 10, where the dots refer to

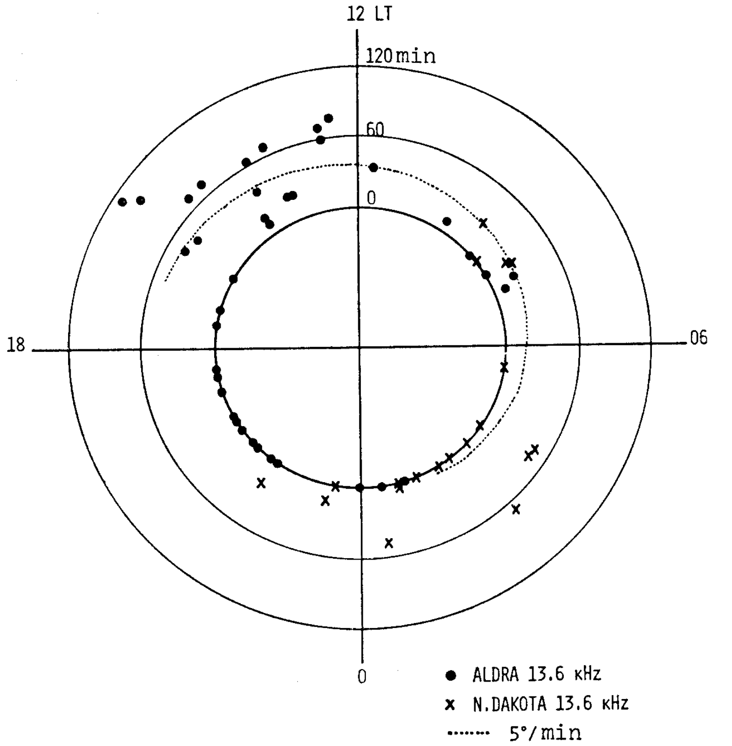

Fig. 10. Local time distribution of the delayed time of the precipitation onset from the onset of the nightside magnetic bay, deduced from the phase anomalies on ALDRA (dots) and N. DAKOTA (crosses). The broken curve indicates the time needed for electrons to drift eastward at speed of 5°/min after injected in the midnight sector.

ALDRA and the crosses to N.DAKOTA. The simultaneous onset during the night hours implies that the energetic electrons of energy more than 150 keV are precipitated from the magnetotail, along with the lower-energy electrons ($E<10$ keV) responsible for the auroral electrojet currents. We note that the nightside precipitation is not symmetrical about the midnight meridian. The precipitations in the evening to pre-midnight sector are restricted to the ALDRA and GBR paths and sometimes to ALDRA path alone (Fig. 7b). This suggests that the energetic electron precipitation takes place near the auroral oval in the evening to pre-midnight sector. In the post-midnight sector, on the other hand, the precipitation extends to the lower latitude region where the N.DAKOTA path traverses and sometimes to the sub-auroral region as evidenced by the phase anomalies on NLK.

The delay of the onset of the precipitation in the morning and afternoon sectors is due to the eastward drift motion of the energetic electrons which have been injected from the magnetotail into the midnight sector. The drift speed has been obtained in the previous section as about 5°/min. The dotted curve in Fig. 10 shows the delay time obtained when the electrons injected in the midnight sector drift eastward at a speed of 5°/min. This drift speed is in good agreement with 4°/min obtained by HARGREAVES (1968) from the absorption data. HARGREAVES (1968) suggested that the energy required for the electrons drifting at the speed of 4°/min was 120 keV on the assumption that the drifting shell is in 7 earth radii distance. It should be noted that the energy of the precipitating electrons derived from the phase anomaly on the ALDRA signal, $E>150$ keV, is in the same order as 120 keV.

The precipitation in the morning sector is frequently simultaneous with the night-side magnetic bay (Fig. 5). The source of the energetic electrons may be in the outer radiation belt in the morning sector (JELLY and BRICE, 1967). SVENNESSON (1972) also gave an example of the VLF phase anomaly suggesting that the electrons of energy more than 200 keV originate in the radiation belt in the morning sector. The frequent precipitation in the afternoon to evening sectors detected by the VLF phase anomaly (Fig. 5) is in no agreement with the riometer observation which showed the minima in the substorm-associated absorption around the dusk hours (HARGREAVES, 1968; JELLY, 1970), while the frequent precipitation in the morning sector is observed in both observations. This discrepancy may suggest that only the high-energy electrons ($E>150$ keV) reach the afternoon sector after eastward drift. Such high energy electrons will cause VLF phase anomalies, but no appreciable increase in the absorption (WESTERLUND and REDER, 1973). It is concluded that the high-energy electrons ($E>150$ keV) are precipitated at all local times with maxima at 0800, 1630 and 2230 LT.

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